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Optical test of the DS1 prototype concentrating surface

R. Blázquez[a,]*, J. Carballo[a], P. Cadiz[a], M. Frasquet[a], M. Silva[a], P. Fontela[b], J.C. Ballesteros[b]

[a] *CTAER, Solar Department, Paraje Retamares s/n, 04200, Tabernas – Almería (SPAIN)*
[b] *Endesa Generación, Ribera del Loira 60, 28042, Madrid (SPAIN)*

Abstract

This paper describes the optical test of the DS1 prototype concentrating surface carried out by CTAER. The DS1 is a parabolic Stirling dish developed under the framework of "SOLARDIS" project. The aim of this investigation was to characterize the DS1 prototype optical parameters. For this purpose the real and the theoretical flux distribution was calculated on a target placed at the focal length and a comparison between them reported about the value of some relevant parameters. The theoretical flux distribution was obtained by photogrammetry technique and ray tracing tools; the real flux distribution was measured by photographic flux mapping technique of lunar images. The results comparison showed that the dish surface had an average optical error of 2.5mrad (it includes errors due to deviation of surface normal vector and the effect of the specularity, but it does not include the sun shape error) and an estimated spillage value of 7%, for this geometry.

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Keywords: solar; concentration; flux mapping; optical; distribution; moon; phtogrammetry;

1. Introduction

Measurement of flux distribution on a target, which is placed at the focal length of solar concentrating systems, has become a standard technique for the optical characterization of concentrators. In order to improve the optical

* Corresponding author. Tel.: +3-467-4-125390;
E-mail address: rosa.blazquez@ctaer.com

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efficiency and the receiver durability, it is necessary to check that the flux distribution on the focal region is similar to the design flux distribution once the system is built. The theoretical flux distribution is a design parameter and it is usually estimated from an ideal surface and a list of errors which is estimated according to the state of the art. It is essential to check if the real distribution fits with the theoretical distribution, since deviations in the estimated optical errors can cause hot points on the receiver surface and/or very high levels of spillage.

For real flux distribution measurements on the focal plane, problems related to high concentrated energetic flux and materials resistance can be found, so the photographic flux mapping technique of lunar images is very useful because much less energy is concentrated using the radiation from the moon. Therefore, the advantage of the lunar images experiment is that the moon has a similar angular width to the solar image and the high heat flux associated with the solar radiation is avoided.

There are a few reports that talk about the lunar flux mapping [1,2] but flux density distributions were not reported in these studies. The first attempt to measure the flux distribution using images of a full moon projected onto a flat target was described by Thomas and Whelan [3]. Later, a video graphic flux mapping of a lunar image has been used to characterize the focal flux distribution of the ANU 400 m^2 "Big Dish" solar dish, for this purpose was employed a CCD image camera, photovoltaic cell and a LED light [4].

2. DS1 solar dish

DS1 is a parabolic Stirling dish developed under the framework of "SOLARDIS" project. The concentrator shown in Figure 1 is a parabolic dish with a circular aperture of 9.2 m diameter, 5.54 m focal length and an effective area of 55 m^2.The collector surface is composed by 40 facets of glass-metal and the structure is mounted on a central pedestal. The collector was designed for the installation of a Stirling engine of 10 kW_e.

DS1 is equipped with a 2 axes tracking system (elevation, azimuth) which rotates the collector surface and the motor Stirling around the central pedestal. During the lunar test campaign, the tracking was achieved under manual control.

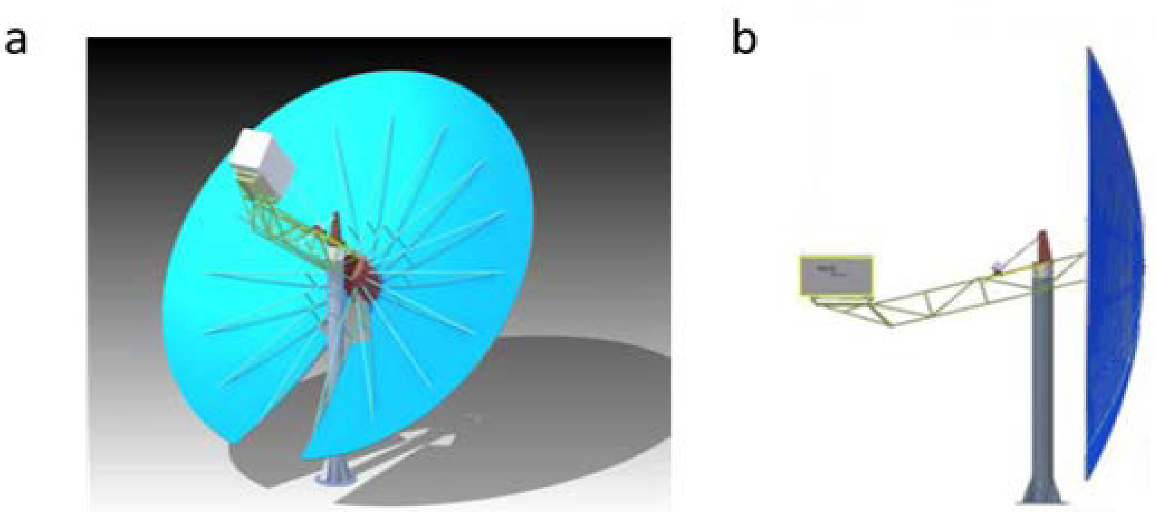

Fig. 1. (a) 3D Model; (b) Profile view.

Fig. 2. DS1 solar dish.

3. Methodology

3.1. Surface characterization by photogrammetry

Photogrammetry is a simple procedure that allows the characterization of surfaces through pictures taken. The use of photogrammetry to analyze the solar concentrator's geometry was described by Pottler et al. [5] and Shortis and Johnston [6,7]. The use of CCD cameras is not required and the measurement accuracy depends on several factors. The most relevant factors are the camera sensor, the point grid size and the redundant number of pictures taken. For this test, 468 retroreflective targets, 39 code targets, 4 calibration bars and 1 reference triangle were used. The measurements were made in 4 different collector elevations (0, 30, 60 and 90 degrees). In order to verify that the structure was rigid enough, 350 pictures for each measurement were taken. All pictures were taken with a calibrated Nikon D3X camera. The measurements were analyzed by AICON DPA (post processing software) and a point cloud was achieved for each measurement.

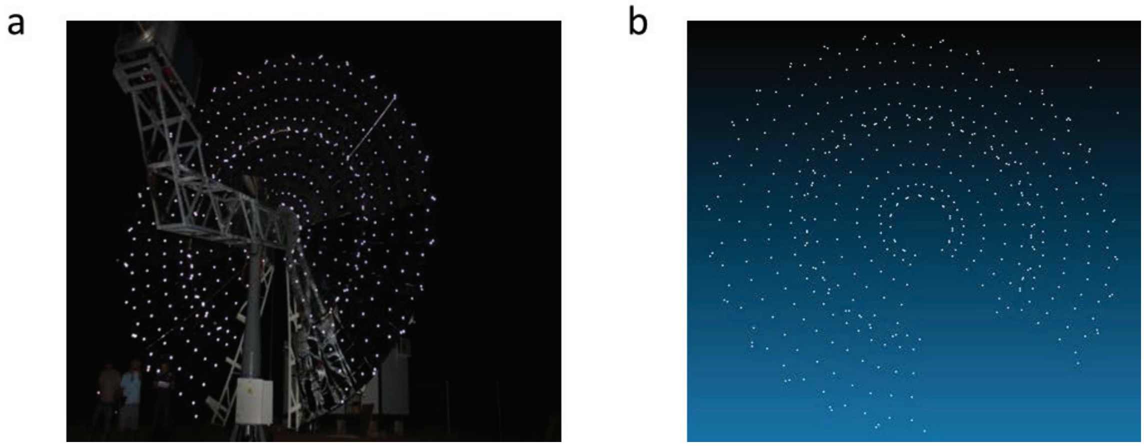

Fig. 3. (a) DS1 with retrorreflective targets on the surface; (b) Point cloud obtained by photogrammetry

3.2. Best fit

The point clouds were fitted to an ideal parabolic curve in order to know the best fit parameters (Equation 1). The fitting was carried out for the four different elevation measures.

$$z = A^2(x+C)^2 + A^2(y+D)^2 + B \tag{1}$$

Where *"A"* is the focal length, (*x,y,z*) are the space coordinates of a point in the reference system and (*C,D,B*) is the parabolic dish origin offset. The aperture plane is parallel to the plane formed by the x and y axes. Table 1 shows the fitted parameters.

Table 1. Fitted parameters

Collector elevation	A (mm)	B (mm)	C (mm)	D (mm)	RMS (mm)	FOCAL LENGTH (m)
0º	0.0068	-24.25	-314.89	-716.86	6.92	5.41
30º	0.0068	-25.38	-316.42	-722.00	6.85	5.43
60º	0.0068	-26.35	-316.60	-728.96	6.87	5.44
90º	0.0068	-26.86	-316.43	-740.45	6.93	5.45

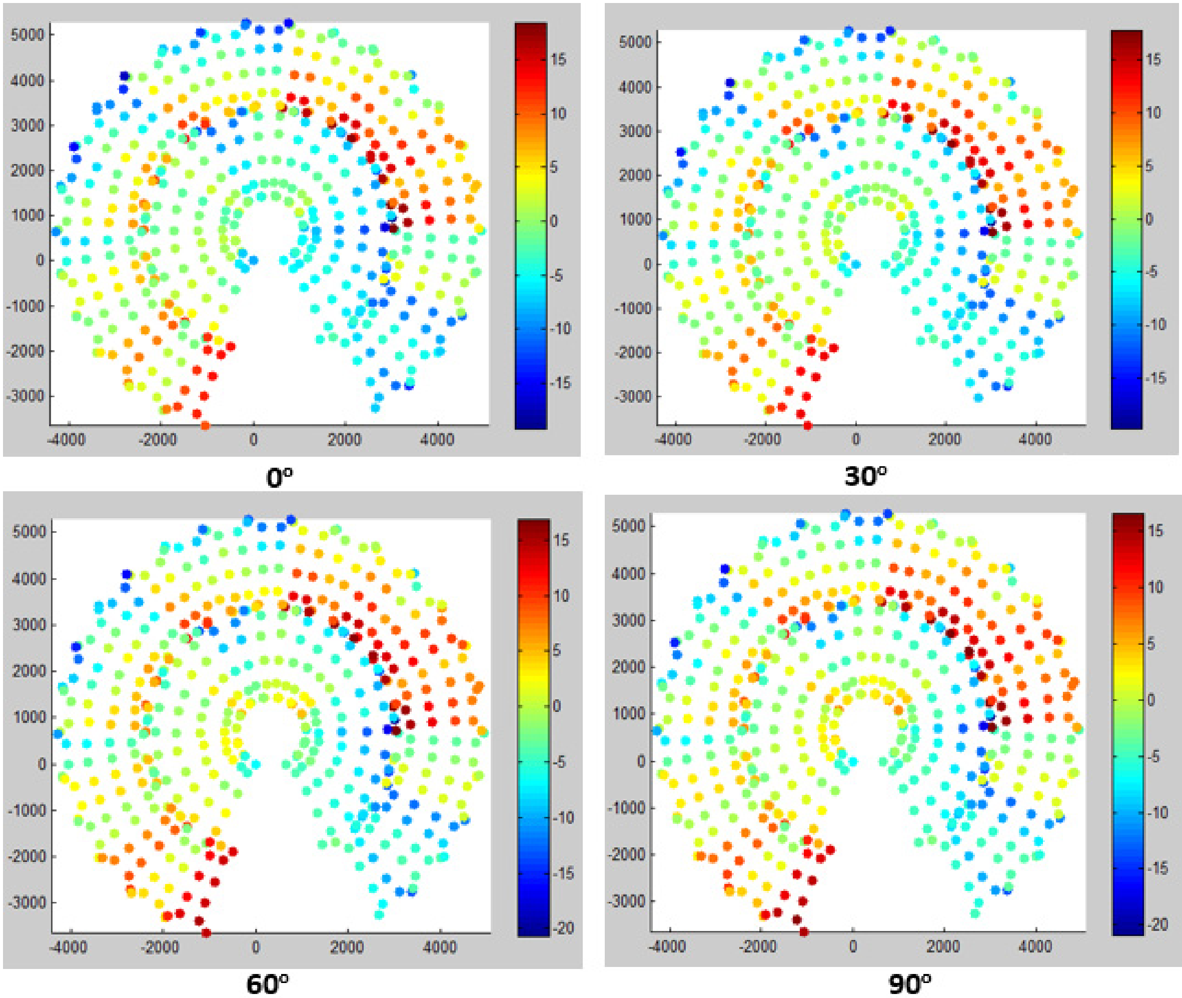

Fig. 4. Offset in the aperture plane normal direction (z axis)

As shown in Figure 4, the offset of each point varies from 0 to ±20 mm. These deviations are kept constant for the four different elevations, which indicates that the parabolic dish structure is solid enough.

3.3. Simulation by ray tracing tools

The theoretical flux distribution was computed using ray tracing tools, in particular TONATIUH software [8]. The optical system simulated was composed by an ideal surface with the parameters obtained in the previous fitting and one flat target located on the focal of the ideal surface. The sun shape used to simulate the moon was Pillbox 4.65 mrad and 0.001 W/m^2 of DNI.

The optical error is the variable that has the greatest influence in the optical quality of the concentrator, in Tonatiuh called "slope error". The optical error in Tonatiuh includes errors due to deviation of surface normal vector and the effect of the specularity, but it does not include the sun shape error. In addition, the tracking error was not taken into account in this case, because it was necessary to modify the concentrator control logic, which was not accessible, for its measurement. A usual value for the global optical error (including the sun shape) in a parabolic dish is around 7 mrad [9].

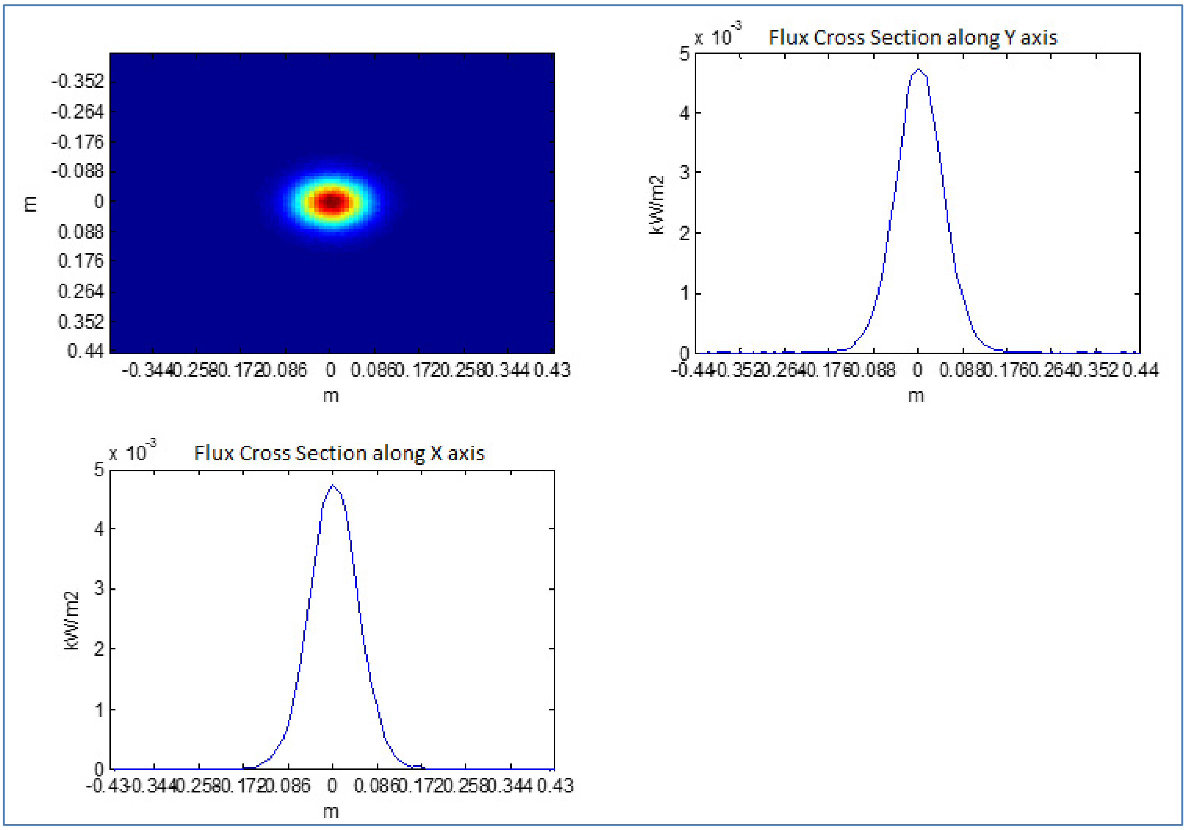

Fig. 5. Flux distribution example (kW/m2) for an ideal concentrator with the parameters got in the previous best fit (5.43 m focal length, 30º elevation and 3.5mrad optical error)

3.4. Lunar flux mapping

The cost benefit of lunar flux mapping must be weighed against a number of disadvantages, among others: operation is only possible on a few nights per month with near full moon conditions; the flux distribution cannot be measured in the full range of conditions which prevail in on-sun operation (e.g. ambient temperature and sun elevation); the acquired images must be corrected for the difference between the lunar angular diameter (at the time of the test) and the conventional solar diameter, which can differ by up to 7%. However, the main advantage is to avoid the use of a cooling system, which makes it very useful. The lunar test was carried out at night, on July the 23th 2014. Pictures were taken on a flat target located on the cavity aperture while the system was in lunar tracking. A Canon EOS 500D camera and a neutral filter were used. In the post-processing the pictures were treated and the lunar flux distribution was obtained and normalized.

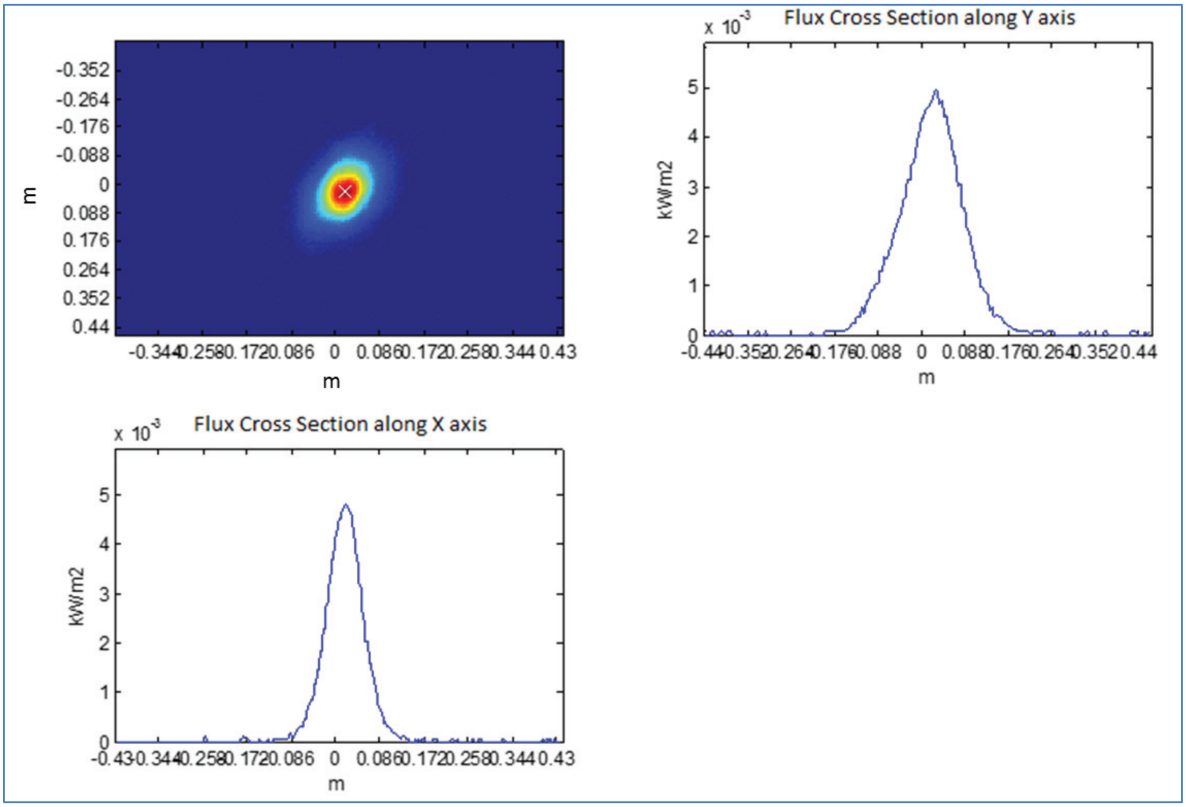

Fig. 6. Experimental flux distribution obtained (kW/m^2)

4. Comparison between experimental and theoretical distribution

Since the ideal flux distribution on the target can be considered to be a Gaussian distribution, the standard deviation can be used to compare different distributions on the target, instead of peak intensity, so the problems of flux calibration with the moon intensity are avoided [4]. Standard deviation distribution represents the optical surface error. Scaling factor should be used to compare and compensate the errors due the dish mirror reflectivity. If the lunar flux intensity is accurately measured, the scaling factor could be considered like the average surface reflectivity but for this test campaign could not be accurately measured.

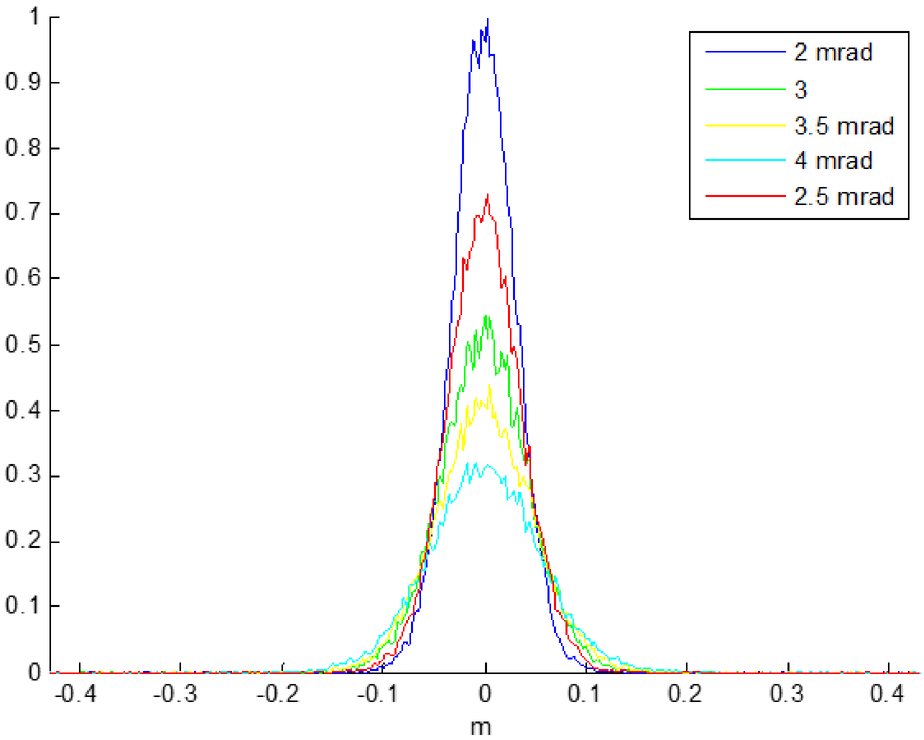

Fig. 7. Flux cross section along the Y axis for different optical errors

The simulated distribution that better fits to lunar flux distribution (experimental measured flux) is the distribution obtained for a slope error of 2.5mrad and 71% of scale factor. Considering the error associated with the sun shape, the global optical error takes a value of 6.83mrad.

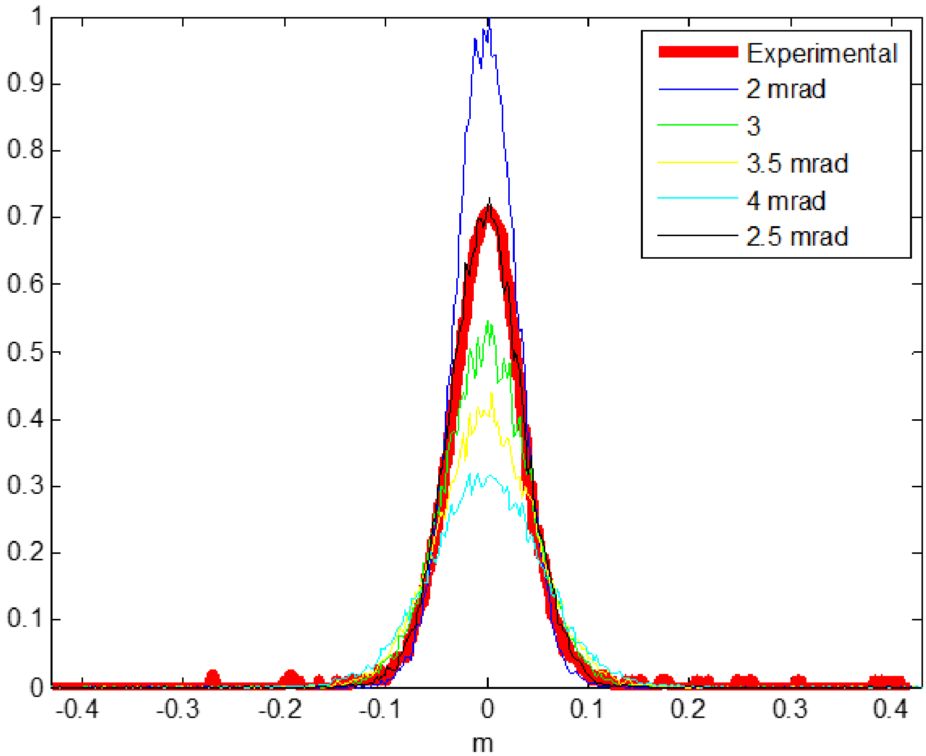

Fig. 8. Superposition of theoretical and experimental flux on the target distribution along the X axis

This global optical error value corresponds to a spillage of 7% for DS1 geometry; it means that the 93% of the concentrated energy by the collector crosses the cavity aperture (0.09 of radius).

5. Conclusions

The aim of this paper was the characterization of the main optical features of DS1 concentrator through the comparison of the theoretical and measured flux distribution on the focal plane.

Photogrammetry proved to be a useful method that allows to know the surface geometry. Lunar flux mapping showed a Gaussian distribution curve, which was analyzed and compared with the theoretically predicted flux distributions through simulations with ray tracing tools, to give a value of optical quality of the concentrator.

The comparison revealed that the best fit for both curves, the measured and the theoretical one, was for a value of 2.5mrad standard deviation and 71% scale factor. This value considered errors introduced during the measurement, such as an uneven layer of dirt on top of the concentrator's surface, which had not been cleaned and errors introduced in taking images. Considering the error associated with the sun shape, the value of the global optical error is 6.83 mrad. The spillage was estimated in a 7%.

Despite all these factors, the value obtained for the optical error is consistent with the existing literature [8], so it was concluded that the DS1 solar dish had an optical quality in line with the market and the current state of the art in these technologies.

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